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Evaluation and Refinement of Test Methods Used for Measuring Fire Hazards of Shipboard Hull Insulations and Mattress Insert Foams

B. T. Lee

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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EVALUATION AND REFINEMENT OF TEST METHODS USED FOR MEASURING FIRE HAZARDS OF SHIPBOARD HULL INSULATIONS AND MATTRESS INSERT FOAMS

B. T. Lee

Abstract

A quarter-scale room fire test developed at NBS was used to help develop a preliminary approach for fire hazard assessment of wall-ceiling combinations of hull insulation materials. The quarter-scale test has been refined to include measurement of heat release rate, smoke, and carbon monoxide. In addition, polyphosphazene foam insulations were evaluated with this test.

The quarter-scale test was also modified for testing mattress insert materials, including polyphosphazene foam. Existing tests, used for measuring total heat, rate of heat release, and smoke production, were also used to evaluate these materials. Heat release rate measurements with the Ohio State University apparatus and smoke measurements with the ASTM E 662 test, modified for horizontal placement of specimens, gave adequate evaluation of the fire hazards of mattress insert materials.

Key words: Fire hazards assessment; foam (materials); heat release rate; hull insulation; interior finishes; mattresses; polyphosphazene foams; small-scale fire tests; smoke.

1. INTRODUCTION

1.1 Thermal Insulation

The fire performance requirements presently used by the Navy for bulkhead and overhead insulation are stated in MIL-STD-1623D(SH) [1][1]. This standard calls for a maximum flame spread limit of 25 by the ASTM E 84 tunnel test [2] and some limit, depending on the material, on the smoke developed by the same test. A compartment fire study of hull insulations has demonstrated that flame spread tests, such as the E 84 test, often do not adequately reflect the flashover potential of these insulations [3]. In that study, the insulation was used to line the bulkhead and overhead of a 3.0 m x 3.0 m x 2.3 m high compartment; a 62 kW gas burner in one back corner served as the ignition source. In one case where an insulation satisfying the above fire performance requirements was used, flashover (full fire involvement) of the compartment occurred in 46 seconds. The same report described the development of a quarter-scale compartment fire test and evaluated its ability to follow full-scale compartment fire behavior. The study concluded that the quarter-scale test was useful as an economical screening tool for evaluating a large number of materials. It offered advantages similar to the full-scale test in that for any given fire initiation source, the ignition, flame spread, heat release, and smoke generation characteristics of the insulation, along with the complex effects of the thermal reinforcement on these properties as the fire grows, are all included. However, the report recommended that final approval of an insulation still be based on the results of a full-scale test.

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[1]Numbers in brackets refer to the literature references listed at the end of this report.

There are also problems associated with smoke measurement from the E 84 test which measures the integrated smoke obscuration and not optical density. Smoke production from the test can not be quantified since the volumetric flow through the tunnel is not measured. In addition, differences in thermal exposure, ventilation, flame spread, and spatial distribution and coagulation of the smoke particles between the E 84 test and the full-scale compartment fire test make it difficult to relate smoke measurements between the two tests. Recent modifications to the quarter-scale compartment fire test have enabled its use to measure the production of smoke and carbon monoxide and rate of heat release from the fire.

1.2 Foam Mattress Materials

The fire hazard requirements in the Navy's purchase specification MIL-M-18351F(SH) [4] call for testing of mattress insert (core) materials with the ASTM E 162 radiant panel [5] for flammability and with the ASTM E 662 smoke density chamber [6] which measures the specific optical density of the combustion-generated smoke. These tests may not adequately reflect the fire hazard of the material. First, it has been demonstrated [3] that tests such as the E 162 radiant panel and E 84 tunnel tests, when used for measuring flammability of hull insulations, could assign a "fire safe" rating to a potentially high fire hazard material. There is no reason to expect that these tests are any more reliable for evaluating mattress insert materials. Second, with the E 662 or the E 84 tests, it is difficult to extrapolate data to smoke levels representative of room fires of the same materials. Third, material configuration and orientation affect the burning behavior of materials. The material

is positioned vertically in the E 662 test. In the E 84 test, the material specimen is attached on the ceiling. Neither position is representative of the actual placement of mattresses in a room. Finally, differences in the thermal exposure, ventilation, flame spread, and spatial distribution and coagulation of the smoke particles complicate any attempt to derive correlations between the laboratory tests and the compartment fire test of the same material.

Use of the E 662 test by itself could unfairly penalize materials which would otherwise perform well under more realistic conditions, and it could favor other materials which may not be as fire safe. In this test, the entire surface of the material specimen is subjected to a constant flux of 25 kW/m^2 and contributes to the production of smoke. The smoke density measured by that test must be scaled to the area of fire involvement in the room. Unfortunately, this area of involvement cannot be easily determined. For mattress materials exposed to a modest size ignition source inside a room, one material may partially burn with considerable production of smoke per unit affected surface area. The overall smoke, however, may be less than that from another material which generates less smoke per unit affected surface area but which burns so rapidly that the material becomes fully involved by the fire.

Improved E 662 procedures have been developed to help assess more realistically the fire hazard of materials. The test can be modified for horizontal placement of mattress specimens to more closely simulate the actual orientation. Also introduced was the use of mass optical density, the optical density per unit path length multiplied by the volume of the test chamber and divided by the mass of the material consumed during the E 662 test. Mass optical density values from the

test could give an estimation of the smoke produced from the same material burning inside a room, providing the free volume and mass of material consumed in the room were known or could be estimated.

Although smoke obscuration and surface flame spread are important, a primary concern should be the rate of heat release from the burning mattress. Fire tests in a simulated fully-furnished shipboard berthing compartment [7] have shown that the heat released from the bedding and mattress alone could cause flashover of the compartment. Sometimes potential heat measurements [8] are used to indicate the level of hazard to the compartment. This neglects the rate at which this heat is released in the space. A material can have a high potential heat but release it at such a slow rate that it has little effect on the fire development. Laboratory tests for measuring the rate of heat release of materials are available [9,10]. One such test, the OSU calorimeter [10], is found at many laboratories throughout the United States. Differences in thermal exposure, ventilation, and fire spread can complicate correlation of the heat release rate data from calorimeter-type tests with the degree of fire buildup in the compartment fire test. However, such a correlation has been demonstrated for a limited number of mattress types [11].

Another approach to predicting the heat release rate and thus the potential for room flashover is to perform tests with scaled-down mattress specimens inside a reduced-size enclosure. Mattress fire tests in 1973 [12] showed that the qualitative behavior of full-scale mattress burns can be predicted from fire tests of scaled-down mattress specimens. That

study also recommended the development of a small-scale test to measure the rate of smoke production of mattress materials in order to compare the smoke levels which would be achieved in a controlled ventilation compartment involved in a mattress fire. In a subsequent study [13], the quarter-scale compartment fire test, used for screening shipboard hull insulation [3], was modified for testing mattress specimens. In that study, the modified quarter-scale test and its full-scale counterpart test were performed on three types of mattresses: vinyl-covered cotton batting with innerspring, vinyl-covered polyurethane with innerspring, and vinyl-covered solid core polyurethane. The dimensions of the bed frame and the bedding in this quarter-scale test were reduced by a factor of four, except for the thickness of the frame and the thickness of each bedding item which remained unchanged. One-quarter, one-half, and full thickness mattresses were used. For the one-quarter thick mattresses, there was not enough fuel for good simulation. Fires with the full thickness mattresses were abandoned because of the extra burning area of the specimen edges and because the height of the mattress became too close to the ceiling. This extra burning surface together with the closer proximity to the ceiling tended to obscure potential fire hazard differences between the three types of mattresses. It was found that a one-half thickness mattress appeared to have the best potential for simulating full-scale fire behavior as measured by the temperature rise of the gases flowing out from the room. When mattress thicknesses other than one-quarter scale were used, the length and width of the bed spread and sheet were lengthened to permit the same scaled overhang distance from the floor. The modified quarter-scale test has also been used to evaluate insulative barriers as a method of protecting polychloroprene core mattresses [14]. That study concluded that the use of low density noncombustible insulations does not upgrade the fire performance of

polychloroprene mattresses. Another area where this quarter-scale test may be applied effectively would be in an investigation of the effect of shipboard mattress ticking and bedding on mattress fire development. Studies have been performed to analyze the role of ticking and bedding on mattress flammability [12,15-19]. These investigations showed that, in general, bedding did influence the burning of the mattress [15,16,17]. The role of ticking was uncertain, with the ticking playing a minor role in the fire growth in two [15,18] of the four studies reviewed [12,15, 18,19]. The effect of ticking and bedding on mattress fire spread appeared to depend upon the materials used and upon the fire exposure from the ignition source.

Two tests are being developed at NBS to more accurately measure the heat release rate from burning upholstered furniture and mattresses using the oxygen consumption technique. These are a bench-scale calorimeter, used to test small representative horizontal specimens, and a full-size furniture calorimeter. The former will be used to provide input data on mattress products for the mathematical room fire models which are being developed. Tests with the furniture calorimeter will be used to evaluate these analytical models.

1.3 Objectives of Study

The purpose of the present study is to evaluate existing laboratory tests for accurate measurement of the fire hazard potential of hull insulation and mattress insert (core) materials and to develop new tests if necessary. Usually a mattress is evaluated with ticking and sometimes with bedding in place. However, in accordance with the Navy's

request, mattress insert materials are tested without ticking nor bedding. Specifically, the objectives are:

(1) to further develop the NBS quarter-scale room fire test for room lining and furnishing materials to include measurement of heat release rate, smoke, and carbon monoxide;

(2) to develop a preliminary approach for fire hazard assessment of wall-ceiling (bulkhead-overhead) combinations of hull insulation materials;

(3) to evaluate the OSU calorimeter as means for measuring the fire hazard of mattress insert (core) materials;

(4) to evaluate the ASTM E 662 test method, modified for horizontal placement and for mass loss measurement, for measuring the smoke hazard of mattress insert materials;

(5) to evaluate the fire hazard potential of some polyphosphazene foam hull insulations; and,

(6) to assess various candidate shipboard foams as alternative shipboard materials for the standard polychloroprene cushioning material currently in use.

2. FACILITIES AND EXPERIMENTAL TESTS

2.1 Hull Insulation

2.1.1 Experimental Facilities

Two quarter-scale test enclosures were used in this study. Each enclosure was 0.76 m x 0.76 m x 0.61 m high and scaled a 3.0 m x 3.0 m x 2.4 m high room. One enclosure consisted of a 6.4 mm thick aluminum alloy shell, which was positioned over a 6.4 mm steel floor. Aluminum alloy was chosen to provide a realistic heat sink and substrate for the bonding of the Navy hull insulations to be tested. The other enclosure was fabricated from 15.9 mm thick gypsum board held together at the edges with 3.2 mm thick angle iron. This latter enclosure was used for interior finish materials requiring spaced studs behind the material. Each enclosure had a doorway opening of 0.49 m x 0.43 m high based on physical modeling principles and empirical adjustments developed earlier [3]. A 76 mm x 76 mm diffusion flame gas burner, positioned 76 mm above the floor in one back corner, served as the ignition source and was left on throughout the test period. Methane gas was metered to the burner at a flow corresponding to a heat release rate of 1/16 of the rate of the full-scale burner, based on previously developed physical modeling principles [3].

A 0.61 m x 0.91 m hood, having an exhaust capability of 0.18 m^3/s, was employed over the front end of the quarter-scale enclosure to collect the exhaust from the fire. A 1.22 m long, 0.152 m diameter vertical stack having an inlet orifice of 83 mm was connected to the hood. The orifice was used to increase turbulent mixing of the exhaust. Smoke

attenuation of a light beam was measured at 0.55 m above the inlet. Neutral optical density filters were used to calibrate the light sensor over the range of optical densities from 0.04 to 3.0. Air temperature, velocity, and concentrations of oxygen, carbon dioxide, and carbon monoxide were measured in the stack at a position 1.02 m above the inlet, where the exhaust was found to be well mixed. Temperature was measured with a type K thermocouple made from 0.51 mm diameter wire. Velocity was monitored with a pitot-static tube probe. Oxygen concentration was sensed by a paramagnetic analyzer. Nondispersive infrared analyzers were used to record the concentrations of carbon dioxide and carbon monoxide. From these measurements, the rate of heat release, the mass flow of carbon monoxide, and the quantity of smoke generated from the fire were determined.

Air temperatures in the quarter-scale enclosures were monitored at 25, 51, 102, 203, 305, 457, and 610 mm down from the center of the ceiling and at 25, 51, 102, 203, 254, and 356 mm down from the top of the doorway. Temperatures were measured using type K thermocouples fabricated from 0.05 mm diameter wire. Thermal radiation incident on the lower part of the room was monitored with a water-cooled, total heat flux gauge of the Gardon type. Crumpled newspapers on the floor were used to indicate if and when the irradiance was sufficient to ignite light combustible materials in the lower portion of the room. This stage of the room fire buildup is often referred to as flashover.

The full-scale room did not conform to a 3.0 m x 3.0 m x 2.4 m high room having a 0.76 m x 2.03 m high opening at the middle of one wall as originally planned. Due to a recommended change by the ASTM committee on standard full-scale room fire testing, the standardized room

dimensions now are 2.4 m x 3.7 m x 2.4 m high with the same size opening at the middle of the 2.4 m wide wall. This change should have little effect on the fire development as the floor area decreased by only 4 percent, and the air flow into the room depends mainly on the doorway opening, which remained unchanged. Consequently, a room having the standardized dimensions was used. The walls and ceiling of the room were covered with 6.4 mm thick aluminum alloy. A 0.305 m x 0.305 m diffusion flame gas burner, using methane gas and located 0.30 m from the floor and snug against one back corner, served as the ignition source. As with the quarter-scale test, the burner was left on for the duration of the test. The test room was located adjacent to a large 3.66 m x 4.88 m exhaust collector hood having an exhaust capacity of about 3.0 m^3/s. The stack to the hood was instrumented for the measurement of smoke, temperature, velocity, oxygen, carbon dioxide, and carbon monoxide. Optical density of the smoke was measured photometrically in the stack. Neutral optical density filters were used to calibrate the light sensor over the range of optical densities from 0.04 to 3.0. Air temperature was measured with a type K thermocouple made from 0.51 mm diameter wire. Velocity was monitored with a pitot-static tube probe. Oxygen concentration was recorded with a paramagnetic analyzer. Carbon dioxide and carbon monoxide were measured with nondispersive infrared analyzers.

In the full-scale room tests, two different size type K thermocouples, fabricated from 0.05 mm and 0.51 mm diameter wires, were used to measure air temperatures at 0.10, 0.50, 0.90, 1.30, and 1.78 m below the doorway and at 0.10, 0.60, 1.20, 1.80, and 2.34 m below the center of the ceiling. The larger thermocouples were less subject to breakage from falling debris but had slower response and were more sensitive to thermal radiation errors. Hence, they were used for backup measurements.

Carbon monoxide was measured also at 0.30, 0.70, and 1.20 m below the top of the doorway with nondispersive infrared analyzers. A water-cooled flux gauge of the Gardon type was used to measure the irradiance on the floor. Crumpled up newspapers on the floor were used to indicate if and when flashover occurred.

2.1.2 Room Fire Tests

Figure 1 shows a representative quarter-scale room fire test and its corresponding full-scale test of an interior finish material. The interior finish materials used for the room fire tests are shown in Table 1. The polyphosphazene foam (PZ) is a developmental bulkhead material, and various formulations of the foam were evaluated in the room fire tests. However, the scarcity of the PZ materials precluded their use for the assessment of the rating procedure proposed in this report. In the evaluation of this rating procedure and in the development of a system for combining ratings for wall and ceiling materials, forty-four quarter-scale tests were performed using four different materials. These materials were fibrous glass (FG), poly (vinyl chloride)/nitrile rubber foam (PVCN), gypsum wallboard (GB), and prefinished lauan plywood (PW). FG and PVCN are commonly used on board submarines and surface ships. GB and PW, on the other hand, are commonly used in shore facilities and in residential housing; these were included to assure that the test materials selected for the evaluation of the rating procedure covered a wide range of fire properties. These forty-four tests are listed in Table 2, along with the wall and ceiling finish materials used in each test. In each test, air temperatures

were measured along the vertical centerline of the doorway and along the height of the room below the center of the ceiling. The flux to the floor and the time to room flashover, if it occurred, were also monitored. However, measurements of heat release rate, smoke, and carbon monoxide were not taken for this series of 44 tests. The room environment in 41 of the tests was conditioned at a temperature between 24 and 29°C and at a relative humidity between 30 and 40 percent just prior to testing. Prior to each test, the exterior of the room was surrounded with a plastic envelope and the room environment was controlled with two 610 mm x 305 mm x 51 mm high pans filled with a saturated aqueous solution of calcium chloride for two days. In the remaining three tests, the relative humidity was controlled at 22, 63, and 76 percent with dry calcium sulfate and saturated aqueous solutions of calcium nitrate and sodium carbonate, respectively. Several ignition exposures were used for this series of 44 tests. The rate of heat release settings used for the burner were 1.4, 2.8, 5.6, and 11.3 kW corresponding to methane gas flows of 38, 75, 150, and 300 mℓ/s at 20°C and 100 kPa, respectively.

In the fire hazard evaluation tests of polyphosphazene foams and their comparison with the tests of a PVC-nitrile rubber foam, the currently used hull insulation, fourteen quarter-scale tests and three full-scale tests were performed. These tests are shown in Tables 3 and 4. Radiant flux at the floor along with air temperatures at the doorway and inside the room were measured in all of the tests. Measurements of heat release, smoke, and carbon monoxide were taken in the vertical stack, discussed in Section 2.1.1, for test numbers 78-14 through 78-18. Test 78-13 had these measurements taken in a horizontal stack. These stack measurements were not taken for the earlier tests 78-1 through

78-12 and for test 79-35. However, CO at the top of the doorway was monitored for tests 78-1 through 78-12. Heat release rate, smoke, and carbon monoxide measurements were recorded for all three full-scale tests. The smoke meter malfunctioned for full-scale test 1. Since the polyphosphazene insulations were closed-cell foams, they were assumed to be unaffected by humidity conditions. Thus, no conditioning of these insulations was undertaken prior to testing. The rates of heat release used in these quarter-scale tests were 5.6, 8.4, and 11.3 kW, corresponding to methane flows of 150, 225, and 300 mℓ/s, respectively. A methane flow of 3.6 ℓ/s corresponding to 135 kW was used for the full-scale test.

2.2 Mattress Inserts

2.2.1 Experimental Facilities

A quarter-scale test enclosure constructed with light-weight (220 kg/m^3) inorganic fiberboard, having the same dimensions as the enclosures used to test hull insulation, was used to fire test mattress insert specimens. Inorganic fiberboard was used to minimize heat losses to the structure and at the same time assure the integrity of the structure for extended usage in fire testing. In each of these fire tests, a single 165 mm x 483 mm x 51 mm thick nominal size foam specimen was positioned on a simulated bed frame directly over a diffusion flame burner, which was located at the center of the floor. The burner surface was 76 mm x 76 mm in area and was flush with the floor. The burner used methane gas at a flow of 225 mℓ/s corresponding to 8.4 kW. This latter rate of heat release was arbitrarily chosen to represent an ignition severity large enough to adequately assess the fire hazard of mattresses, but not so large as to overwhelm the mattresses being evaluated. A rate of 8.4 kW corresponded to approximately 3/8 of the rate of heat input required for room flashover and could represent the exposure from a fire in a lower berth of a three-man bunk or a fuel spill under the bunk. The bed frame was 0.48 m x 0.17 m x 0.13 m high and was fabricated from 3.2 mm thick x 12.7 mm angle iron with a 19.1 mm x 44.5 mm x 3.2 mm hardware cloth for mattress support. The head of the bunk was centered against the back wall.

The same 0.61 m x 0.91 m hood and associated instrumentation, discussed in section 2.1.1, were used for measuring heat release rate, smoke, and carbon monoxide. Air temperatures were measured at 25.4 mm and 50.8 mm below the top of the doorway and at 25.4 mm and 76.2 mm

below the center of the ceiling using type K thermocouples made from 0.05 mm diameter wires.

The same full-scale room used for testing hull insulation was lined with 15.9 mm gypsum board for testing mattress inserts. In each test, a 1.94 m x 0.76 m x 0.10 m to 0.14 m thick nominal size mattress was supported by a bed frame directly over a 0.305 m x 0.305 m porous plate diffusion flame burner located at the center of the floor. The porous surface of the burner was positioned 0.18 m above the floor. The burner used methane gas at a flow rate of 3.6 ℓ/s, corresponding to 135 kW, or 16 times as large as the burner fuel flow in the quarter-scale test as required by previously developed scaling criteria [3]. The bed frame was 1.94 m x 0.76 m x 0.51 m high and was constructed from 3.2 mm thick angle iron with 1.6 mm diameter wire forming a wire grid having 51 mm x 102 mm spacing for mattress support. The head end of the bunk was pushed against the back wall.

As in the room fire tests of hull insulation, smoke, air temperature, velocity, oxygen concentration, carbon dioxide, and carbon monoxide were also measured in the stack of the large hood. Carbon monoxide was sampled at the same locations in the doorway as before. Thermocouples placed in the same doorway and room interior locations were used to monitor air temperatures in the mattress fire tests.

2.2.2 Mattress Fire Tests

Figure 2 shows a representative quarter-scale room fire test and its corresponding full-scale room fire test of a mattress insert material.

The mattress insert specimens used in this study are shown in Table 5. Polyurethane R was chosen as a reference material having a high hazard potential. Polychloroprene RP was formerly an acceptable habitability foam for use on board submarines and surface ships. However, the current specification [2] calls for a "low-smoke" version of polychloroprene foam, and polychloroprene RP does not qualify. Polychloroprene DPSC was procured from Defense Personnel Support Center, Philadelphia, PA and was supposed to be the same as the RP. The remaining materials were all potential candidate replacement materials for the polychloroprene RP. Thirty-four quarter-scale room fire tests of mattress specimens were performed. Five were preliminary tests used to provide insight as to what to expect and to further check out the adequacy of the test instrumentation and experimental setup. The other 29 tests are indicated in Table 6. The specimens were approximately 480 mm long, 170 mm wide, and 50 mm thick and had uniform material properties throughout each specimen, except for the polychloroprene CC and polyphosphazene. The polychloroprene CC consisted of laminated layers of foam, and the polyphosphazene foam came in 12.7 mm thick sections. Consequently, four pieces of polyphosphazene had to be wired together to give the proper test specimen size. Sixteen full-scale tests were performed. These are shown in Table 7. The full-scale polychloroprene CC mattress also consisted of laminated layers. The polychloroprene DPSC mattress insert was allegedly the same as the polychloroprene RP and thus was not evaluated as part of the full-scale series. Full-scale polyphosphazene mattress inserts were not available; therefore, only quarter-scale tests of the material were performed.

2.3 Calibration of Exhaust Collector Hoods for Heat Release Rate Measurement

The exhaust collection stack for the quarter-scale test was calibrated for measurement of heat release rate using the quarter-scale

methane burner, which was also used as the ignition source in the room hull insulation fire tests, positioned directly under the hood as well as inside the room. The burner had a heat release rate of 16.5 kW based on the flow of methane to the burner. The rate of heat release of the burner can also be determined from the measurement of the volume flow rate and the oxygen depletion of the air passing through the stack [21]. The calculated value based on this latter technique was 17.1 kW, or 4 percent larger than the actual value based on the methane flow rate, for the burner located directly under the hood. When the burner having the same methane flow rate was positioned at the center of the floor, the calculated value was 15.8 kW, or 4 percent smaller than the actual size. The $\pm$ 4 percent accuracy is well within an estimated 10 percent experimental uncertainty in measuring volumetric flow and oxygen levels in the stack. For the full-scale exhaust system, the stack was calibrated in a similar manner. Using a heat release rate of 210 kW from the burner, the calculated value was within $\pm$ 7 percent of the actual rate. For rates above 500 kW, a study [22] indicated that the flow velocity across the cross-section of the full-scale stack was highly non-uniform, and the heat release rate measurements had to be multiplied by 0.77 to give the actual values. The calibration from that study was used for the calculations of heat release rate above 500 kW in this report.

2.4 Quantification of Smoke from Room Fire Tests

The attenuation of a light beam by smoke is proportional to the concentration of smoke, C_s (kg/m^3), the path length, L (m), and the attenuation characteristics of the smoke particles expressed as a

specific extinction coefficient, K (m^2/kg). Thus, the initial beam intensity I_o is attenuated to I according to

$$\frac{I}{I_o} = e^{-KC_sL} \tag{1}$$

The measurement is often expressed as an optical density, O.D.,

$$O.D. = \mathrm{Log}_{10}\left(\frac{I_o}{I}\right) \tag{2}$$

In the present series of tests, it was desired to evaluate the total amount of smoke produced over the duration of the test. This can be expressed in terms of the total extinction cross-section, E (m^2), where

$$E = KC_s\ V = 2.3\ V\left(\frac{O.D.}{L}\right) \tag{3}$$

and V(m^3) is the total air volume filled with smoke, and C_sV is the total smoke mass released. Since $\dot{v}$ (m^3/s), the volume flow of smoke-filled air from the room, and the quantity O.D. change during the test, E is determined by integrating over the duration of the test, t(s), or

$$E = \frac{2.3}{L}\int_o^t \dot{v}\ (O.D.)\ dt \tag{4}$$

Equation (4) can also be related to measurements performed in the ASTM E 662 test with the smoke density chamber [6]. The quantity E is equivalent to the product of the specific optical density measured in that test and the specimen surface area employed in the test. Equation (3) can be used to estimate the average O.D. per meter beyond the room of fire origin if the smoke is dispersed over a known volume and the effects of smoke deposition and coagulation are neglected.

2.5 Laboratory Tests of Fire Properties

The mattress insert materials were also evaluated by laboratory fire tests for rate of heat release, potential heat, and smoke production. Both the NBS calorimeter [9] and the OSU calorimeter [10] were used to measure rate of heat release. The potential heat test [8] and the smoke density chamber, modified for mass loss measurement and horizontal placement of the test specimen [11], were employed for measuring potential heat and smoke generation of these materials.

3. RESULTS AND DISCUSSION

3.1 Hull Insulation

3.1.1 Proposed Rating System

In the fire hazard assessment study of interior finish materials, the test material fully lines the walls and ceiling of the quarter-scale test room, and an ignition source is positioned in one back corner of the room. A material is given a letter rating related to the energy of the ignition source required for flashover in a 3.0 m x 3.0 m room lined with the material and a number rating based on the time in seconds to reach flashover. The letter assignments are based on the occurrence or nonoccurrence of flashover at five different ignition source gas flow rates in the quarter-scale model tests. Preliminarily, these rates are chosen to be 1, 1/2, 1/4, 1/8 and 1/16 of the heat input required to flash over a space having the walls and ceiling lined with fire-exposed fibrous glass with a glass cloth facing over a time period of 300 s or longer. Fire exposed fibrous glass is selected because it has virtually all of its organic binder burned away and absorbs a minimal quantity of

heat from the fire. These heat release rates correspond approximately to 350, 175, 88, 44 and 22 kW for a 3.0 m x 3.0 m x 2.4 m high room. The 350 kW level is roughly equivalent to the rate of heat generated from a slow burning uphostered chair, and the 22 kW rate is representative of a small wastebasket fire. The heat release rate for the ignition source used for the quarter-scale experiments would scale with the ratio of the floor areas or 1/16 of the full-scale rates [3]. The method of assigning the letter rating from A to F is outlined below.

Fraction of Gas Flow Rate Required for Flashover	Does Flashover Occur? A	B	C	D	E	F
1	No	Yes	Yes	Yes	Yes	Yes
1/2	No	No	Yes	Yes	Yes	Yes
1/4	No	No	No	Yes	Yes	Yes
1/8	No	No	No	No	Yes	Yes
1/16	No	No	No	No	No	Yes

It is possible for an interior finish, e.g., gypsum wallboard, to obtain an A rating. Gypsum wallboard has a much higher thermal conductivity, thereby allowing greater heat loss from the room, than the fibrous glass. Consequently, a room lined with gypsum wallboard would not flash over at the highest gas flow rate. Fibrous glass at the same rate setting would flash over and have a B rating. Once the lowest level for which flashover will occur i6s determined, the time to flash over required for the numerical rating should be established at the next higher gas flow. This precaution will avoid borderline cases when flashover may occur at a deceptively late time. The exceptions are that a material rated A has no numerical rating since flashover does not occur, and the time for a B rated material is determined at a flow rate of one.

As an example, a 3.0 m x 3.0 m x 2.4 m high room fully lined with a material rated B/160 would not be expected to flash over with a 175 kW source in the corner. However, it would be expected to flash over in around 160 seconds in the case of a 350 kW source in the corner of a room having an open doorway. Thus, there is some predictive aspect included in the rating which is not the case, e.g., for the ASTM E 84 flame spread classification.

A summary of the results from the 44 tests that were performed to give a preliminary assessment of the proposed rating procedure for room lining materials is given in Table 2. The data in Table 2 were used to give the matrix shown in Table 8 for rating individual and combinations of wall and ceiling materials used in this study. From an analysis of Table 8, it appears that if the wall and ceiling materials have different ratings, then the combination will often have an intermediate rating. For example:

(a) the use of a D or E rated material on the walls together with a class A or B material on the ceiling could cause the wall and ceiling material combination to have a C or D rating;

(b) a class D or E finish on the ceiling together with a class B wall lining could cause the combination to have a C or D rating; and,

(c) wall finish has a greater effect than ceiling finish on the fire performance of such material combinations when they are evaluated under the test conditions used in this study. For example, the A rated GB wall finish together with class D or E ceiling finish resulted in class B combinations.

3.1.2 Evaluation of Polyphosphazene Foams

In the fire hazard comparison study of PZ foam with PVCN (B2) foam, the room fire test results in Table 3 clearly showed the superiority of PZ foam. For the same ignition exposure, the rooms lined with PZ (tests 78-2 and 78-13) did not experience flashover over a 900 s test period, whereas the compartments covered with the PVCN (tests 78-1 and 79-35) attained flashover after only 51 to 83 s. Even when PZ was substituted for PVCN (B2) only on the ceiling, as in test 78-5, flashover was averted. A more recent formulation of the PVCN foam, PVCN (B2II), did not cause flashover of the quarter-scale room when a 5.6 kW ignition exposure was used. That test was not instrumented. A fully instrumented test of the B2II insulation, run 78-17, was then performed with no occurrence of room flashover. Although six formulations of PZ (APC-2, APC-4, APC-G and H, APN, and CAPN) were used, the fire buildup, as evidenced by the peak doorway and interior air temperatures, was about the same in fire tests of most of the formulations. The interior air temperatures were similar for tests 78-2 and 78-13 using the APC-2 and APC-G foams, respectively. In tests 78-4, 78-11, and 78-14, with the APC-2, H, and APC-4 formulations respectively, similar doorway air temperatures were reached. However, test 78-14 with the APC-4 foam achieved a much higher room air temperature. Test 78-15 with the APN foam achieved a

somewhat lower doorway air temperature but an even higher room air temperature than that in test 78-14. CAPN foam is a chlorinated polyphosphazene significantly different from the other PZ foams. Test 78-16 of the CAPN resulted in severe localized heating (flame impingement) of the thermocouples near the ceiling with only a slightly higher doorway air temperature than those temperatures in the tests of the other PZ formulations. Increasing the ignition exposure to about one-half of the rate of heat release needed for flashover, as in test 78-3, resulted in flashover of the PZ (APC-2) foam. Test 78-12 with the PZ(H) foam showed that a typical decorative shipboard paint could also affect PZ foam to the extent that temperatures and CO concentrations similar to flashover conditions, such as in test 78-1, were achieved in the test even though the flashover indicator did not ignite. The duration of the high temperature pulse in that test may have been too short to affect ignition of the indicator. Three coats of the same decorative paint over the CAPN foam resulted in room flashover at 114 s.

3.1.3 Comparison of Quarter-Scale and Full-Scale Room Fire Tests

Only three full-scale tests of PZ were performed due to the scarcity and cost of the material. Table 4 compares the results of the full-scale tests with their counterpart quarter-scale room tests. Quarter-scale tests 78-14, 78-15 and 78-16, corresponding to full-scale tests 1, 5, and 6, respectively, had peak interior air temperatures over 600°C, a temperature which is often an indicator of flashover [23]. However, the doorway air temperatures for these quarter-scale tests were significantly below 400°C. A study [24] has demonstrated that a doorway temperature of 400°C or higher together with an interior air temperature of at least 600°C are both required before flashover occurs with the quarter-scale

test. Consequently, the quarter-scale room tests 78-14 to 78-16 suggested borderline room flashover situations with test 78-16 with the CAPN being the worst of the three tests. The same studies [23, 24] have shown that the full-scale test is more severe than its quarter-scale counterpart. Thus, there was a reasonable chance for all three full-scale tests and, particularly, the counterpart of test 78-16, i.e., full-scale test 6, to achieve flashover. Of the three full-scale tests, only test 6 reached flashover. Once flashover is reached, there could be an order of magnitude increase in the peak rate of heat release and in the production of CO and smoke from the fire. Table 4 shows that tests 1 and 5 had peak heat release rates between 120 and 240 kW and a peak CO generation of 1.3 to 3.6 g/s. Smoke production for test 5, when expressed in terms of the extinction cross section E discussed in section 2.4, was 520 m^2 after 300 s. In contrast, test 6, which reached flashover at 85 s, had a peak rate of heat release of 2130 kW and a maximum rate of 34 g/s CO at the time of flashover and a smoke production of 5170 m^2 after 300 s. It is interesting to note that the combined heat release rate value of 375 kW from the burner and burning foam in full-scale test 1 could have also caused flashover of the room if that rate had been maintained for a longer period [23].

3.2 Mattress Insert Materials

3.2.1 Room Fire Tests

A summary of the test results from the 29 quarter-scale room fire tests is given in Tables 6 and 9. Data from the 16 full-scale room tests are presented in Tables 7 and 9. The full-scale results in Table 7 indicated that the peak heat release rate of 2250 kW from the polyurethane R mattress insert greatly exceeded the rate required to cause flashover of the room. This was confirmed by the doorway and interior

air temperatures exceeding 900°C. Fire tests of the polychloroprene RP, polyurethanes SP and SP-H, and the polyimide IH resulted in peak heat production rates between 88 to 109 kW. The peak total heat release rate, which included the 135 kW from the gas burner, was about 230 kW for these tests. The measurement accuracy at this rate level was about $\pm$ 15 kW, meaning differences in heat release rates among these mattress foams were too small to be ascertained with the instrumentation system. The remaining tests in Table 7 had rates equal to or less than 70 kW. Table 9 shows that the polyurethane R resulted in a smoke extinction cross section E of 1050 m^2 over the 180 s which it took to fully consume the mattress. Heavy dark smoke was generated in the polychloroprene RP test compared with a modest quantity of smoke produced in the test with the SP-H. The extinction cross section E for smoke generated over the first 300 s was 2150 m^2 for the RP and 420 m^2 for the SP-H. All of the remaining mattresses resulted in E values of less than 190 m^2 for the 300 s duration. After 1800 s, the RP and SP-H mattress tests had E values of 6960 and 2200 m^2, respectively, compared with values less than 1140 m^2 for the other mattress foams. Table 7 shows that the polyurethane R had the highest peak mass flow rate of CO, i.e., 34 g/s, among the mattresses tested. The tests with the SP-H, RP, and IH had maximum values of 2.7, 1.5, and 1.5 g/s, respectively. The rest of the tests in Table 7 had peak CO rates of less than 1.0 g/s.

In a Navy berthing area, there is approximately one three-tier bunk with a 0.10 m thick mattress at each level for each 9.3 m^2 of floor area [25]. If all three 0.10 m thick mattresses were burning at the same time, the air and room surfaces would reach higher temperatures than if only one mattress was burning. The thermal feedback between adjacent

mattresses and the enhanced feedback from the hotter air and room surfaces would reinforce the burning rate of each mattress. Thus, the heat release rate for the three mattresses would be more than three times greater than the values given in Table 7 for individual mattresses. The total heat production rate in the room would be the sum of the rates for the ignition source and the three mattresses. For polychloroprene RP and polyurethane SP, this total heat release rate would exceed 435 kW. These calculations further suggested that the fire involvement of the polychloroprene mattresses in a 3.0 m x 3.0 m room could also cause room flashover, especially when the rest of the bedding such as the sheets, pillows, and blankets were also involved. In fact, this has been demonstrated in full-size room fire tests with three-man bunks [7].

The quarter-scale room fire tests ranked the mattress inserts, using the rate of heat release as the basis, in the following order of decreasing fire hazard: (1) polyurethane R; (2) polyurethanes SP-8 and SP-H; (3) polychloroprene RP, including the DPSC, and polyurethane SP; and (4) others. Whereas the full-scale tests indicated that the RP behaved much like the SP-H in terms of peak heat release rate, the quarter-scale tests showed the RP having about one-half of the rate for the SP-H. The burning behavior of the polychloroprene RP and DPSC specimens in the quarter-scale tests was significantly different from the combustion of the full-size mattresses. The quarter-scale specimens, 0.05 m thick, exhibited surface flaming combustion but had no observable smoldering combustion, whereas the 0.10 m thick full-size mattresses exhibited both surface flaming combustion and glowing combustion in the core of the mattress during the test. Apparently, the increased thickness

resulted in less heat escaping from the core, thereby allowing the smoldering combustion to be self-sustained. This smoldering in the full-size mattress could contribute significant heat release and could account for the differences in heat release rates between the quarter-scale and full-scale tests of the polychloroprene RP. This might also have been the case for the polyurethane SP. The greatest differences in heat release rates and air temperatures between the quarter-scale and full-scale tests were for the polyurethane R. Once again, this was due to differences in specimen thickness between the quarter-scale and full-scale tests. The problem is compounded by the fact that the full-scale polyurethane R mattress was used in its original thickness of 0.14 m and was thus almost three times thicker than its corresponding quarter-scale mattress. This compared with a full-scale to quarter-scale mattress thickness ratio of two for the shipboard and candidate mattresses. The thicker full-scale mattresses burn longer with the fire heating the air and room surfaces over a longer period. This results in a more pronounced and prolonged thermal feedback from the flame, hot air, and heated surfaces to the burning mattress, thereby further enhancing its rate of combustion. The middle part of the thin polyurethane R mattress in the quarter-scale test was quickly and completely consumed before the rest of the mattress was involved. In the full-scale mattress fire, much of the middle section was still burning by the time the whole mattress was involved. The relative portion of mattress area still burning during the peak full fire development was less in the quarter-scale test. Consequently, the quarter-scale test of the polyurethane R produced much less heat per unit time and less smoke than its full-scale counterpart during their peak fire intensities for each square meter of surface. In fact, the quarter-scale test produced less smoke obscuration than the polychloroprene RP, which was not the case in the full-scale tests.

Nevertheless, the quarter-scale test can differentiate between the good and poor fire risk mattress insert materials.

There was one mattress insert where two successive tests of the material resulted in significantly different results for smoke obscuration. Tests 13A and 13B of the laminated polychloroprene CC showed that there was much more smoke generation in test 13A than in test 13B. This was in agreement with visual observations. Nonuniformity in foam formulation could have caused this difference. The higher smoke generation was not observed in the full-scale tests of the material.

3.2.2 Laboratory Fire Tests

Table 10 compares data from the potential heat test and the OSU and NBS rate of heat release calorimeters with results from the quarter-scale and full-scale room tests. The listing of materials in Table 10 are given in the order of decreasing rate of heat release from the full-scale room fire tests. The ranking of the four materials having the highest heat release rate, i.e., R, SP-H, RP, and SP were ranked in the same order by the quarter-scale test, the OSU calorimeter, and the NBS calorimeter. The OSU calorimeter had the same problem that the quarter-scale test had in that the RP gave heat release rates which were much lower than the rates for the SP-H. As explained in section 3.2.1, this could have been a consequence of the specimen thickness. The OSU calorimeter had a higher value for HS-2 than expected. Similarly, the quarter-scale test gave values that appeared high for the HS-2 and CC foams. The problem could also be in the reliability of measuements below 100 kW in the full-scale tests. However, none of these discrepancies were

major ones. More serious problems arose with correlations with the potential heat data and with the NBS calorimeter results. The results of the potential heat test did not correlate with the behavior of the mattress materials in the full-scale room fire tests. For example, the polyurethane HS had a potential heat of 47500 J/g, much higher than the values for polyurethane R and polychloroprene RP, but performed well in the room fire tests. With the NBS calorimeter data, the peak rate and maximum 60 second averaged rate for polyurethane HS suggested that the HS material would perform more like polychloroprene RP than like polychloroprene LS. However, the room fire tests showed that the polyurethane HS behaved like the polychloroprene LS.

Table 9 compares the smoke production data from the E 662 test, modified for horizontal placement of specimens, with the O.D./m and extinction cross section E results from the quarter-scale and full-scale tests. The foam materials in Table 9 are listed in a decreasing order of total smoke generation, as indicated by the extinction cross section values, after 300 s in each of the full-scale tests. Peak values of optical density per meter, or smoke concentration, could indicate the instantaneous peak levels in each test, but could not quantify the smoke as a function of time. The O.D./m data from the full-scale tests ranked the polyurethane R as being the worse smoke producing material. However, when total smoke production over a 300 s duration was considered, the chloroprene RP came out worse. Extinction cross-section values in the quarter-scale test were more difficult to measure than in the full-scale test, due to the much lower quantity of smoke produced in the former test. Even if the smoke per unit path length, i.e., concentration, were

the same in the quarter-scale and full-scale stacks, the full-scale test has the advantage in that its path length for smoke measurement is eight times longer. Consequently, the quarter-scale test was unable to quantify the smoke from tests of materials other than the RP and DPSC foams.

When the E values for the full-scale tests are divided by their respective mattress weights consumed by the fire, the resultant ratios should correlate with the specific extinction areas derived from the E 662 test, providing the fire exposures in the two tests are close enough. In this study, correlation with the E 662 test was difficult due to the limited data. The E values were available for the RP, R, and SP-H foams, and these correlated roughly with their respective E 662 specific extinction areas. The E values for the CC, LS, HS-2, and IH foams were too low to be measured with the existing smoke monitoring system. However, visual observations suggested that the total smoke generated in these cases was much less than that for the R and SP-H foams. Since the weight loss for both the HS-2 and R foams was the same, the specific extinction area E/M_s from the room fire with the HS-2 had to be lower than the 420 m^2/kg for the R foam. Furthermore, if the IH foam generated the same total quantity of smoke as did the HS-2 foam, the specific extinction area E/M_s for the IH would be about five times higher than that for the HS-2. This was because the weight of mattress consumed in the IH test was only about one-fifth as great as that for the HS-2. These observations were consistent with the specific extinction areas from the E 662 test for the mattress foam specimens studied. An advantage of using the modified E 662 test is that it affords the resolution of differences beyond the lower range capability of the full-scale measurement, providing the mass loss of the mattresses

is known or can be estimated. Even without this knowledge, the specific extinction area values from the modified E 662 test roughly correlates with the E values from the full-size mattress fires.

4. SUMMARY

1. A possible rating procedure has been demonstrated for measuring the fire hazard potential of individual room lining materials with the NBS quarter-scale room fire test. However, there is a need to evaluate the procedure over a wider range of materials to fully assess its strengths and limitations.

2. The interdependency of wall and ceiling materials in the potential fire hazard rating of room linings has been examined. High fire hazard materials either on the wall or ceiling surfaces could seriously jeopardize the overall rating of the room.

3. Polyphosphazene foam was vastly superior to the poly(vinyl chloride)/nitrile rubber foam B2, the currently used hull insulation on board submarines, in the room fire tests of these materials.

4. The potential heat measurements of the mattress insert materials did not correlate with the full-scale test behavior of these materials.

5. Ranking of mattress insert materials for their potential rate of heat release with the OSU calorimeter was as good as those

using the NBS calorimeter and the NBS quarter-scale room fire test, modified for mattress testing. The limited data suggested that the OSU calorimeter can be useful in screening out high fire hazard materials.

6. Reduced-thickness mattress specimens in the quarter-scale room test could not experience the smoldering combustion found in some full-size mattresses, because the former were not sufficiently thick to retain the heat, necessary to sustain smoldering, from escaping from the core. The reduced thickness could also result in burning patterns different from those observed in full-size mattress fires.

7. The ASTM E 662 test, modified for horizontal placement of the test specimen, was found to give an adequate indicator of the relative smoke generation potential of the mattress insert materials evaluated in the room fire tests in this study.

8. Several candidate mattress inserts were demonstrated to have lower rates of heat release and a lower production of CO and smoke in the room fire tests performed in this study than the polychloroprene RP formerly used on board submarines and surface ships.

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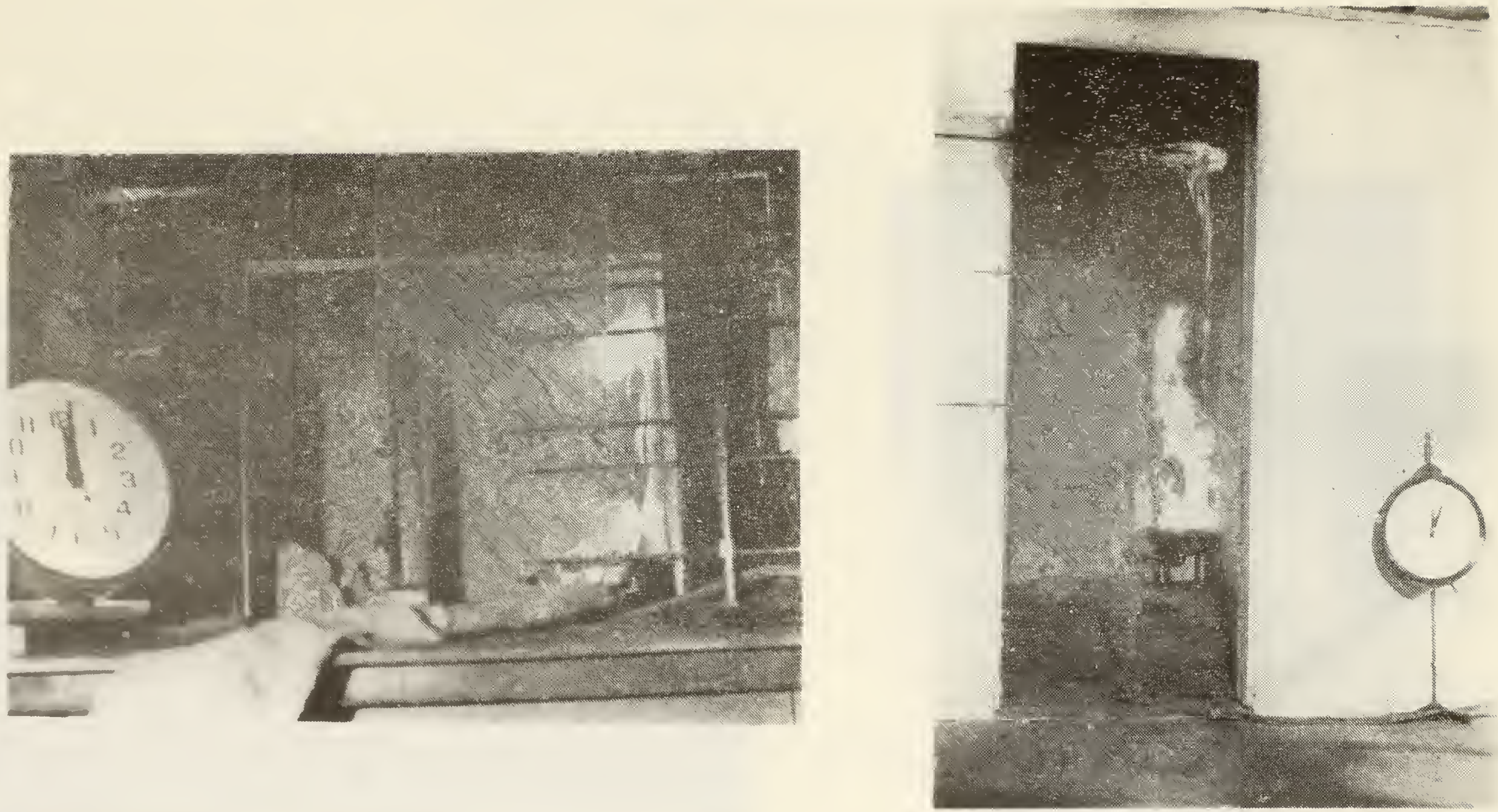

Figure 1. Quarter-scale and full-scale room fire tests of interior finish materials

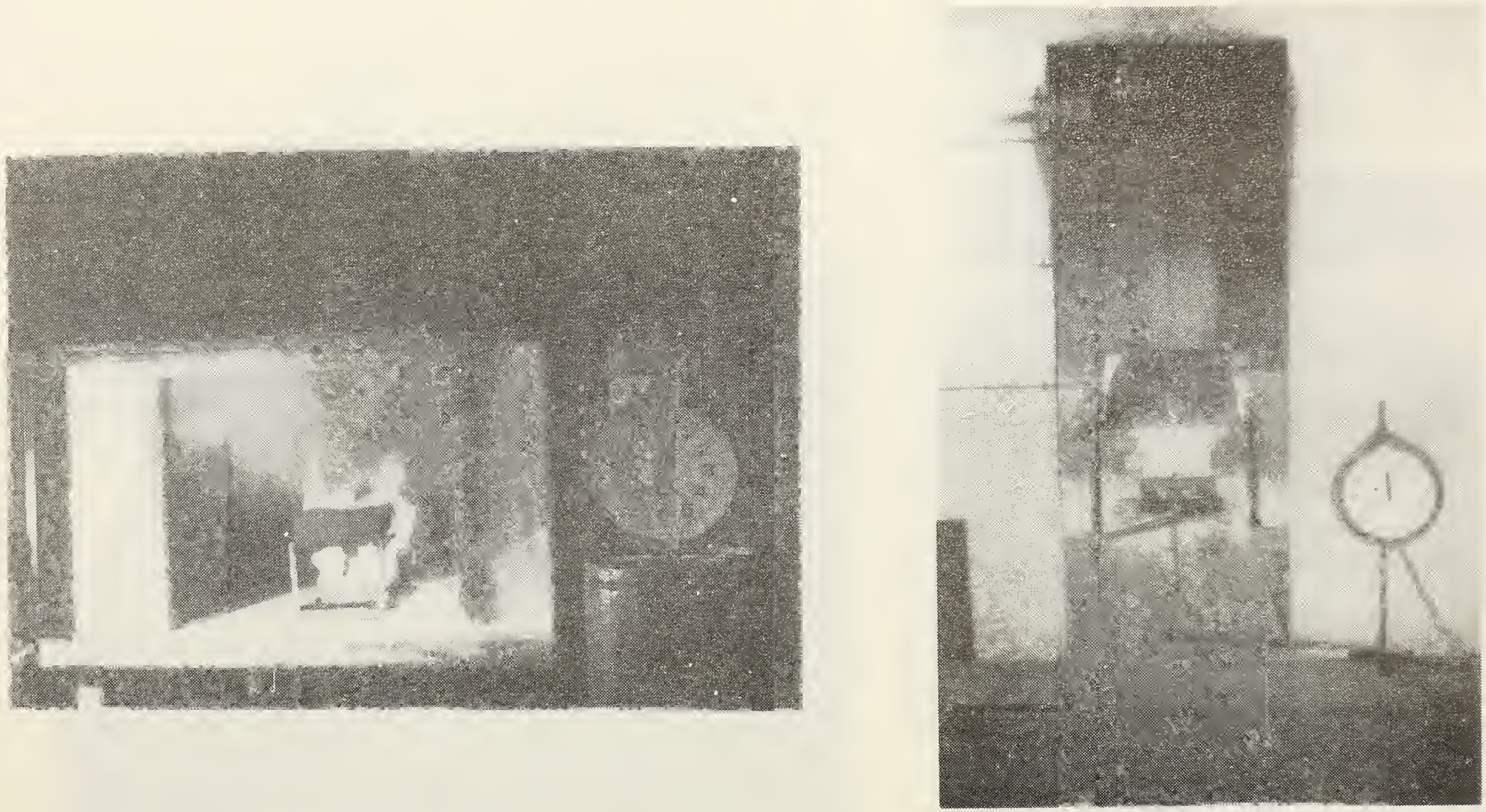

Figure 2. Quarter-scale and full-scale room fire tests of mattress insert materials

Table 1. Interior Finish Materials

Material	Material Specification	Thickness (mm)	Density (kg/m^3)
1. Fibrous Glass, Glass Cloth Surface (FG)	MIL-I-742 C	25.4	64
2. Poly(vinyl Chloride)/Nitrile Rubber Foam (PVCN)	MIL-P-15280	27.0	88
3. Gypsum Wallboard (GB)	--	15.9	930
4. Lauan Plywood, 3 ply, Printed Surface (PW)	--	4.0	--
5. Polyphosphazene (PZ)*	--	12.7	97

*Not used for evaluation of proposed rating procedure for interior finish.

Table 2. Summary of Quarter-Scale Room Fire Tests Used in Rating Procedure

Test	Wall Material*	Ceiling Material*	Burner Heat Release Rate (kW)	Time to Flashover t_f (s)	Floor Flux*** at Time t_f or Time to T_{MI} (kW/m^2)	Doorway Temp. T_D at Time t_f (°C)	Interior Temp. T_I at Time t_f (°C)	Test Conditions: Relative Humidity (%)	Test Conditions: Temp. (°C)	Maximum Doorway Temp. T_{MD} (°C)	Time to T_{MD} (s)	Maximum Interior Temp. T_{MI} (°C)	Time to T_{MI} (s)
79-39	GB	GB	22.5	**	0.4	—	—	38	21	530	433	830	81
79-4	GB	GB	11.3	**	1.4	—	—	34	26	320	600	580	93
79-40	GB	FG	22.5	**	0.9	—	—	38	25	540	468	830	162
79-13	GB	FG	11.3	**	3.1	—	—	32	27	430+	460	620	88
79-41	GB	PVCN	22.5	398	N/A	670	760	37	24	670	398	830	201
79-22	GB	PVCN	11.3	**	N/A	—	—	34	28	350	393	570	113
79-42	GB	PW	22.5	555	2.1	720	790	37	23	870	327	860	456
79-11	GB	PW	11.3	**	6.4	—	—	34	27	420	241	930+	196
79-43	FG	GB	22.5	**	0.8	—	—	37	25	540	117	850	84
79-20	FG	GB	11.3	**	1.5	—	—	34	26	380	311	570	46
79-44	FG	FG	22.5	83	1.8	660	810	35	22	660	83	870	45
79-12	FG	FG	11.3	**	4.4	—	—	34	27	330	202	630	84
79-16	FG	PVCN	11.3	500	16.6	470	700++	36	26	470	500	880	53
79-19	FG	PVCN	5.6	**	1.8	—	—	37	25	240	573	380	472
79-17	FG	PW	11.3	200	18.2	780	690+	35	26	780	200	900+	113
79-24	FG	PW	5.6	325	25.1	840	810	32	28	840	325	850	100
79-29	FG	PW	2.8	**	0.14	—	—	40	24	170	550	240	573
79-21	PVCN	GB	11.3	137	46.3	590	690+	33	26	590	137	860+	69
79-27	PVCN	GB	5.6	**	1.4	—	—	40	26	230	414	420	161
79-23	PVCN	FG	11.3	66	49.8	750	810	32	29	750	66	830	54
79-14	PVCN	FG	5.6	**	4.3	—	—	34	26	290	204	550	130
79-36	PVCN	PVCN	11.3	58	52.8	730++	860	30	27	730++	58	920++	49
79-35	PVCN	PVCN	5.6	83	46.7	680+	730+	34	26	680+	83	870+	59
79-34	PVCN	PVCN	2.8	**	0.3	—	—	32	28	200	468	260+	451
79-30	PVCN	PW	11.3	93	57.7	740+	700	37	25	800+	86	930	67
79-26	PVCN	PW	5.6	192	29.1	630+	660+	35	28	630+	192	860+	150
79-28	PVCN	PW	2.8	**	0.16	—	—	34	28	160	355	250	523
79-7	PW	GB	11.3	183	18.7	740	840+	35	26	740+	180	950	124
79-5	PW	GB	5.6	534	23.4	820	920++	31	27	850	530	920++	534
79-6	PW	GB	2.8	**	N/A	—	—	36	27	110	367	290	187
79-32	PW	FG	11.3	180	19.6	680+	790++	34	29	680+	172	920	112
79-15	PW	FG	5.6	230	18.9	640	890++	35	26	660	227	940+	196
79-18	PW	FG	2.8	**	2.5	—	—	35	27	270	587	650	539
79-25	PW	PVCN	5.6	239	19.9	720+	690+	36	28	720+	239	840+	169
79-31	PW	PVCN	2.8	369	19.2	670	680	36	27	670	369	950	322
79-33	PW	PVCN	1.4	**	N/A	—	—	34	27	90	426	180	238
79-1	PW	PW	5.6	290	14.0	870	740+	76	25	870	290	1000	218
79-10	PW	PW	5.6	272	17.4	770	910++	63	26	770	272	1000	202
79-2	PW	PW	5.6	231	18.7	730+	890+	38	24	860+	210	940	131
79-38	PW	PW	5.6	323	27.3	890+	790++	36	26	890+	323	940	212
79-37	PW	PW	5.6	295	19.3	830+	810++	32	27	840+	279	940	167
79-3	PW	PW	5.6	224	18.3	820+	820++	22	26	820+	224	980	162
79-8	PW	PW	2.8	454	18.5	760	850+	36	28	790	416	970	354
79-9	PW	PW	1.4	**	N/A	—	—	36	28	80	426	160	158

* Description of materials in Table 1.

** No flashover over the test duration of 600 s.

*** Floor flux measured at middle of rear quadrant, away from burner. Flux at time t_f when flashover occurred, otherwise flux given at time to T_{MI} (Max. Interior Temp.). N/A - Not Available.

\+ Peak temperature occurred at 51 mm below top of doorway or 51 mm below center of ceiling.

++ Peak temperature occurred at 102 mm below top of doorway or 102 mm below center of ceiling.

Table 3A. Comparison of Quarter-Scale Room Fire Tests on Polyphosphazene and Poly(vinyl chloride)/Nitrile Rubber Foams

Test	Ceiling Material	Wall Material	Ignition Source (kW)	Test Duration (s)	Time to Flashover (s)	Peak Stack Heat Release Rate, $\dot{Q}_s$ (kW)	Time to $\dot{Q}_s$ (s)	Floor++ Flux kW/m^2	Max.* Doorway Temp. T_1 (°C)	Time to T_1 (s)	Max.* Interior Temp. T_2 (°C)	Time To T_2 (s)
78-1	PVCN(B2)	PVCN(B2)	5.6	55	51	-	-	40.8	530	51	600	51
79-35	PVCN(B2)	PVCN(B2)	5.6	85	83	-	-	38.8	680	83	870	59
78-5	PZ(APC-2)	PVCN(B2)	5.6	900	> 900	-	-	6.5	180**	55	430	79
78-2	PZ(APC-2)	PZ(APC-2)	5.6	900	> 900	-	-	3.3	230	141	300	114
78-13	PZ(APC-G)	PZ(APC-G)	5.6	900	> 900	2.5+++	23	1.8	--	--	310	131
78-17	PVCN(B2II)	PVCN(B2II)	8.4	1200	>1200	6.6	143	4.6	340	160	620	90
78-4	PZ(APC-2)	PZ(APC-2)	8.4	900	> 900	-	-	8.2	340	114	460	102
78-11	PZ(H)	PZ(H)	8.4	900	> 900	-	-	7.3	350	216	470	192
78-14	PZ(APC-4)	PZ(APC-4)	8.4	900	> 900	6.2	47	4.8	340	113	670	61
78-15	PZ(APN)	PZ(APN)	8.4	1200	>1200	4.7	43	3.9	280	1001	700	46
78-16	PZ(CAPN)	PZ(CAPN)	8.4	1200	>1200	10.7	142	7.5	360	155	820	120
78-3	PZ(APC-2)	PZ(APC-2)	11.3	132	125	-	-	30.2	610	125	630	119
78-18	PZ(CAPN) 0-634***	PZ(CAPN) 0-634***	5.6	720	114	120.0	110	32.9	620	114	850	70
78-12	PZ(H) 0-634***	PZ(H) 0-634***	8.4	900	> 900	-	-	7.8	550	114	740	48
	FG+	FG+	5.6						240 ± 10	1200	355 ± 10	1200
	FG+	FG+	8.4						305 ± 10	1200	405 ± 10	1200

* T_1 and T_2 measured 25.4 mm below top of doorway and 25.4 mm below center of ceiling, respectively.
** Low temperature may be due to thermocouple placement greater than 25.4 mm below doorway.
*** Two coats of 0-634 paint used in test 78-12 and three coats used in test 78-18.

\+ Fibrous glass hull board, 25 mm thick and fire-exposed prior to test to eliminate combustible binder material. Test included for reference.
++ Floor flux at time of flashover. Otherwise, at time of maximum interior temperature T_2.
+++ Measurement in horizontal stack.

Table 3B. Comparison of Combustion Products for Quarter-Scale Room Fire Test on Polyphosphazene and Poly(vinyl chloride)/Nitrile Rubber Foams

Test	Ceiling Material	Wall Material	Ignition Source (kW)	Peak Doorway $CO, (co)_d$ (%)	Time to $(co)_d$ (s)	Peak Stack Mass Flow $CO, (co)_s$ (g/s)	Time to $(co)_s$ (s)	Peak Smoke (O.D./m)	Time to Peak Smoke (s)	Total Smoke Generation 300s (m^2)	600s (m^2)	900s (m^2)	1800s (m^2)
78-1	PVCN(B2)	PVCN(B2)	5.6	3.8*	51	-	-	>12*	33	-	-	-	-
79-35	PVCN(B2)	PVCN(B2)	5.6	-	-	-	-	-	-	-	-	-	-
78-5	PZ(APC-2)	PVCN(B2)	5.6	0.9*	75	-	-	4.0*	45	-	-	-	-
78-2	PZ(APC-2)	PZ(APC-2)	5.6	0.1*	420	-	-	0.5*	48	-	-	-	-
78-13	PZ(APC-G)	PZ(APC-G)	5.6	-	-	0.21+	527	0.7+	79	-	-	-	-
78-17	PVCN(B2II)	PVCN(B2II)	8.4	-	-	0.99++	33	2.2++	40	180	240	250	-
78-4	PZ(APC-2)	PZ(APC-2)	8.4	0.9*	108	-	-	0.5*	48	-	-	-	-
78-11	PZ(H)	PZ(H)	8.4	0.8*	66	-	-	0.4*	48	-	-	-	-
78-14	PZ(APC-4)	PZ(APC-4)	8.4	-	-	0.17++	709	2.3++	95	150	310	470	-
78-15	PZ(APN)	PZ(APN)	8.4	-	-	0.59++	21	1.0++	42	60	70	70	-
78-16	PZ(CAPN)	PZ(CAPN)	8.4	-	-	0.87++	142	2.9++	160	180	190	190	-
78-3	PZ(APC-2)	PZ(APC-2)	11.3	3.4*	125	-	-	2.5*	125	-	-	-	-
78-18	PZ(CAPN) 0-634**	PZ(CAPN) 0-634**	5.6	-	-	7.99++	100	65.9++	90	1440	1580	-	-
78-12	PZ(H) 0-634**	PZ(H) 0-634**	8.4	3.8*	105	-	-	3.3*	102	-	-	-	-

+ Test 78-13 had measurements of CO and smoke taken in a horizontal stack connecting the hood. Path length of 0.203 m used for smoke measurement.

++ Test 78-14 through 78-18 had measurements of CO and smoke taken in a vertical stack connecting the hood. Path length of 0.152 m used for smoke measurement.

* CO and smoke measured at the top of the doorway. Path length of 0.24 m used for smoke measurement.

** Two coats of 0-634 paint used in test 78-12 and three coats used in test 78-18.

Table 4A. Comparison of Quarter-Scale and Full-Scale Room Fire Tests on Polyphosphazene Foams

Test	Scale	Ceiling and Wall Material	Ignition* Source (kW)	Test Duration (s)	Time to Flashover (s)	Peak Heat Release Rate $\dot{Q}_s$** (kW)	Time to $\dot{Q}_s$ (s)	Floor++ Flux (kW/m^2)	Max. Doorway Temp. T_1 (°C)	Time to T_1 (s)	Max. Interior Temp. T_2 (°C)	Time to T_2 (s)
5	Full	PZ(APN)	135	1800	∞	120	31	3.6	360	50	500	50
78-15	Quarter	PZ(APN)	8.4	1200	∞	4.7	43	3.9	280	1001	700	46
1	Full	PZ(APC-4)	135	1800	∞	240	61	6.7	510	73	550	67
78-14	Quarter	PZ(APC-4)	8.4	900	∞	6.2	47	4.8	340	113	670	61
6	Full	PZ(CAPN)	135	900	85	2130	85	22.3	670	85	840	80
78-16	Quarter	PZ(CAPN)	8.4	1200	∞	10.7	142	7.5	360	155	820	120
Reference	Quarter	FG+	8.4	-	-	-	-	-	305±10	1200	405±10	1200

* Scaling criteria requires the ignition source in the full-scale test to be 16 times larger than that for the quarter-scale test.

** Ignition burner rates of 135 kW for the full-scale tests and 8.4 kW for the quarter-scale tests have been subtracted from values of $\dot{Q}_s$.

\+ Fire-exposed fibrous glass with organic binder burned off. Test included for reference.

++ Floor flux at time of flashover. Otherwise, at time of maximum interior air temperature T_2.

Table 4B. Comparison of Combustion Products for Quarter-Scale and Full-scale Room Fire Tests on Polyphosphazene Foams

Test	Scale	Ceiling and Wall Material	Ignition* Source (kW)	Test Duration (s)	Peak Doorway CO,$(CO)_d$ (%)	Time to $(CO)_d$ (s)	Peak Mass Flow of CO in Stack, $(CO)_s$ (g/s)	Time to $(CO)_s$ (s)	Peak Smoke (O.D./m)	Time to Peak Smoke (s)	Total Smoke Generation 300 s (m^2)	600 s (m^2)	900 s (m^2)	1800 s (m^2)	At time of flash-over (m^2)
5	Full	PZ(APN)	135	1800	0.17	416	1.3	31	0.82	50	520	600	640	750	-
78-15	Quarter	PZ(APN)	8.4	1200	-	-	0.59	21	1.0	42	60	70	70	-	-
1	Full	PZ(APC-4)	135	1800	0.50	61	3.6	55	-	-	-	-	-	-	-
78-14	Quarter	PZ(APC-4)	8.4	900	-	-	0.17	709	2.3	95	150	310	470	-	-
6	Full	PZ(CAPN)	135	900	3.6	80	34.0	85	2.8	85	5170	5330	5380	-	920
78-16	Quarter	PZ(CAPN)	8.4	1200	-	-	0.87	142	2.9	160	180	190	190	-	-

* Scaling criteria requires the ignition source in the full-scale to be 16 times larger than that for the quarter-scale test.

Table 5. Mattress Insert Materials

Material	Color	Density (kg/m^3)	Full-Scale Size Length (m)	Width (m)	Thickness (m)
1. Polychloroprene CC	Black	113	1.94	0.61	0.11
2. Polychloroprene DPSC	Black	74	—	—	—
3. Polychloroprene LS	Peach	103	1.92	0.61	0.10
4. Polychloroprene RP	Black	74	1.92	0.61	0.10
5. Polyimide IH	Yellow	13.8	1.98	0.61	0.10
6. Polyurethane HS	Cream	131	1.78	0.59	0.11
7. Polyurethane HS-2	Cream	148	1.74	0.60	0.10
8. Polyurethane R	White-Yellow	18.5	1.93	0.61	0.14
9. Polyurethane SP	Grey	65	1.95	0.61	0.10
10. Polyurethane SP-H	Grey	74	1.92	0.61	0.10
11. Polyurethane SP-8	Grey	68	-	-	-*
12. Polyurethane WRG	Cream	133	1.82	0.60	0.11
13. Polyphosphazene	Beige	97	-	-	-*

* No full-scale specimen

Table 6. Quarter-Scale Room Fire Tests of Mattress Insert Materials

Test	Material	Peak Stack Heat Release Rate, $\dot{Q}_s^{+}$ (kW)	Time to $\dot{Q}_s$ (s)	Peak Doorway Temp. T_1 (°C)	Time to Temp. T_1 (s)	Peak Interior Temp. T_2 (°C)	Time to T_2 (s)
1A	Polyurethane R	23.2++	59	350	48	630	30
1B	Polyurethane R	19.5	103	340	94	650	30
1C	Polyurethane R	25.9	42	400	31	580	32
16	Polyurethane SP(8-20-05-1)	8.8	300	250	289	270	306
19	Polyurethane SP(8-20-05-1)	8.1	342	240	340	280	344
21	Polyurethane SP-H	7.7	396	240	402	270	387
4A	Polychloroprene RP	3.2++	210	210	257	330	264
4B	Polychloroprene RP	4.8	187	210	230	320	246
12	Polychloroprene DPSC	4.0	247	200	348	300	354
14A	Polyurethane SP	3.3	420	210	480	260	465
14B	Polyurethane SP	4.0	420	210	417	390	411
13A	Polychloroprene CC	2.1	828	180	540	250	25
13B	Polychloroprene CC	1.2	*	170	591	N/A**	N/A**
17	Polyimide IH	1.2	*	190	739	210	790
20	Polyimide IH	1.2	*	190	939	210	910
15	Polyurethane HS-2	≤0.7	*	190	1137	220	1155
18	Polyurethane HS-2	1.2	*	200	1101	220	1109
3A	Polyurethane HS	≤0.7++	*	170	504	250	67
3B	Polyurethane HS	≤0.7	*	180	360	230	96
5A	Polychloroprene LS	≤0.7++	*	170	480	230	348
5B	Polychloroprene LS	≤0.7	*	170	540	230	504
2A	Polyurethane WRG	≤0.7++	*	170	162	230	378
2B	Polyurethane WRG	≤0.7	*	170	540	250	162
6	Polyphosphazene 7	≤0.7	*	170	462	240	462
7	Polyphosphazene 8	≤0.7	*	170	414	230	246
8	Polyphosphazene 9	≤0.7	*	160	446	220	594
9	Polyphosphazene 10	≤0.7	*	170	252	220	252
10	Polyphosphazene 11	≤0.7	*	160	396	220	276
11	Polyphosphazene 12	≤0.7	*	170	444	220	222
	Burner Alone	8.4	-	163 ± 5	-	227 ± 10	-

* No measurable peak.
** Not available
\+ The heat release rate of 8.4 kW from the burner has to be added to $\dot{Q}_s$ to obtain the total rate. Measurement accuracy was about 4 percent of this total rate, e.g., ± 0.35 kW when the material specimen had no measurable heat release.
++ Determined by chemical galvanic cell.

Table 7. Full-Scale Room Fire Test Data

Test	Material	Peak Stack Heat Release Rate, $\dot{Q}_s$* (kW)	Time to $\dot{Q}_s$ (s)	Peak Doorway Temp. T_1 (°C)	Time to T_1 (s)	Peak Interior Temp. T_2 (°C)	Time to T_2 (s)	Peak CO in Stack Mass Flow (g/s)	Peak CO in Stack Time (s)
1	Polyurethane R	2250	76	940	90	980	88	34.0	137
7A	Polychloroprene RP	100	248	210	857	280	1581	1.3	332
7B	Polychloroprene RP	115	259	200	1613	270	1059	1.7	397
9	Polyurethane SP-H	109	1180	190	810	220	1220	2.7	90
4	Polyurethane SP	100	712	190	790	220	826	< 1.0	-
10	Polyimide IH	88	95	180	1640	210	970	1.5	1025
3A	Polyurethane HS	≤70	-	180	1641	210	1236	< 1.0	-
3B	Polyurethane HS	≤70	-	180	1733	190	1625	< 1.0	-
6A	Polychloroprene LS	≤70	-	180	1695	200	1007	< 1.0	-
6B	Polychloroprene LS	≤70	-	170	1786	210	1407	< 1.0	-
2A	Polyurethane WRG	≤70	-	170	1466	210	1231	< 1.0	-
2B	Polyurethane WRG	≤70	-	170	1330	190	439	< 1.0	-
5A	Polychloroprene CC	≤70	-	160	1599	200	1158	< 1.0	-
5B	Polychloroprene CC	≤70	-	160	1726	180	1287	1.1	1690
8A	Polyurethane HS-2	≤70	-	160	1139	190	1538	< 1.0	-
8B	Polyurethane HS-2	≤70	-	160	1278	200	1436	< 1.0	-
Gas Burner**		135	-	160 ± 5	1800	190 ± 10	1800	0	0

* The heat release rate of 135 kW from the gas burner has to be added to $\dot{Q}_s$ to obtain the total rate. Measurement accuracy was about ± 15 kW at a total rate level of 210 kW.

** 135 kW floor burner with inert inorganic fiber board on the bed frame.

Table 8. Fire Hazard Ratings of Individual Interior Finish Materials and Material Combinations

		CEILING LINING			
		GB A*	FG B/83	PVCN D/58	PW E/283
Wall Lining	GB A*	1 (None) 1/2 (None)** A*	1 (None) 1/2 (None) A	1 (398 s) 1/2 (None) B/398	1 (555 s) 1/2 (None) B/555
	FG B/83	1 (None) 1/2 (None) A	1 (83 s) 1/2 (None) B/83	1/2 (500 s) 1/4 (None) C/< 500+	1/2 (200 s) 1/4 (325 s) 1/8 (None) D/200
	PVCN D/58	1/2 (137 s) 1/4 (None) C/< 137+	1/2 (66 s) 1/4 (None) C/< 66+	1/2 (58 s) 1/4 (83 s) 1/8 (None) D/58	1/2 (93 s) 1/4 (192 s) 1/8 (None) D/93
	PW E/283	1/2 (183 s) 1/4 (534 s) 1/8 (None) D/183	1/2 (180 s) 1/4 (230 s) 1/8 (None) D/180	1/4 (239 s) 1/8 (369 s) 1/16 (None) E/239	1/4 (231 s) 1/4 (323 s) 1/4 (295 s) 1/8 (454 s) 1/16 (None) E/283 Average

* Fire hazard ratings expressed as "A" or letter/time for other than "A" rating.

** Fraction refers to ignition exposure expressed as fraction of gas fuel flow rate needed for room flashover when room is lined with FG material. Parenthesis represents the time to reach flashover at that ignition exposure.

\+ Insufficient PVCN material available for tests at next higher fuel flow rate. However, the times to flashover for these wall-ceiling combinations have to be shorter at the higher flow, but the letter ratings remain the same.

Table 9. Comparison of Smoke Production for Room Fire Tests and Laboratory Tests

Material	Full-Scale Smoke Production: Test No. +	Peak Optical Density Per Meter++ (O.D./m)	Extinction Cross Section E*: 300 s (m^2)	600 s (m^2)	900 s (m^2)	1800 s (m^2)	Wt. Loss of mattress after 1800 s M_s (kg)	Specific Extinction Area (E/M_s) (m^2/kg)	Quarter-Scale Smoke Measurement: Test No. +	Peak Optical Density Per Meter++ (O.D./m)	E*: 300 s (m^2)	600 s (m^2)	E-662 Smoke Density Chamber: Specific Extinction Area** (m^2/kg)
Polychloroprene RP	7A,7B	1.7	2150	4770	5700	6960	4.16	1670	4B	1.64	100	180	1390
Polychloroprene DPSC	-	-	-	-	-	-	-	-	12	1.64	60	190	-
Polyurethane R	1	>2.0	1050	1050	1050	1050	2.48	420	1B,1C	0.52	<25	<50	700
Polyurethane SP-8	-	-	-	-	-	-	-	-	16,19	0.71	"	"	-
Polyurethane SP-H	9	0.3	420	870	1470	2200	3.98	550	21	0.66	"	"	560
Polychloroprene CC	5A,5B	≤0.1	<190	<380	<570	<1140	-	-	13A	0.59+++	"	"	-
Polyimide IH	10	≤0.1	"	"	"	"	0.45	-	17	< 0.2	"	"	270
Polychloroprene LS	6A,6B	≤0.1	"	"	"	"	-	-	5B	< 0.2	"	"	50
Polyurethane HS-2	8A,8B	≤0.1	"	"	"	"	2.46	-	15,18	< 0.2	"	"	40
Polyurethanes HS and WRG	2A,2B, 3A,3B	≤0.1	"	"	"	"	-	-	2B,3B	< 0.2	"	"	-
Polyurethane SP	4	≤0.1	"	"	"	"	-	-	14A,14B	0.26	"	"	-
Polyphosphazene 7-12	-	-	-	-	-	-	-	-	6-11	< 0.2	"	"	-

* Values of extinction cross section given after 300, 600, 900 and 1800 s for full-scale tests and after 300 and 600 s for quarter-scale tests.
** Values of specific extinction area determined using procedure described in reference [11].

\+ When multiple tests are shown, only the averaged values are indicated. No data for quarter-scale tests 1A, 2A, 3A, 4A, 5A, and 20.
++ Smoke optical density measured over path lengths of 1.22 m in full-scale tests and 0.152 m in quarter-scale tests.
+++ Quarter-scale test 13B of the CC foam had an O.D./m <0.2.

Table 10. Comparison of Heat Release Data for Room Fire Tests and Laboratory Tests

Material	Full-Scale		Quarter-scale		OSU Calorimeter	NBS Rate of Heat Release Calorimeter +++			
	Test No.+	Peak Heat Release Rate (kW)	Test No.+	Peak Heat Release Rate (kW)	Rate of Heat Release** (kW)	Peak Rate (kW/m^2)	Peak 60 S Avg. Rate (kW/m^2)	Peak 180 S Avg. Rate (kW/m^2)	Potential Heat (kJ/kg)
Polyurethane R	1	2250	1A,1B,1C	22.9	1.29	780	400	130	29280
Polyurethane SP-H	9	109	21	7.7	0.80	140	120	100	-
Polychloroprene RP	7A,7B	108	4A,4B	4.0	0.46	150	140	120	23100***
Polyurethane SP	4	100	14A,14B	3.7	-	110	100	80	11750
Polymide IH	10	88	17,20	1.2	0.03	<10	<10	<10	-
Polyurethane WRG	2A,2B	≤70	2A,2B	≤0.7	-	70	20	10	9720
Polyurethane HS	3A,3B	≤70	3A,3B	≤0.7	-	140	110	80	47540
Polyurethane HS-2	8A,8B	≤70	18	1.2++	0.12	70	30	20	-
Polychloroprene CC	5A,5B	≤70	13A,13B	1.7	-	20	<10	<10	10930
Polychloroprene LS	6A,6B	≤70	5A,5B	≤0.7	0.06	20	20	20	9610
Polyphosphazene*	-	-	6-11	≤0.7	-	20-120	10-80	10-60	9980-13300

\+ When multiple tests are shown, only the averaged value is indicated.

++ Quarter-scale test 15 of the HS-2 foam has Q_s ≤0.7 kW.

+++ Under exposure of 30 kW/m^2. Values cannot be measured accurately below 10 kW/m^2.

* Polyphosphazenes 7-12 and APC-4.

** Average rate for first 180 s of test for exposed specimen surface area of 100 by 100 mm. Values determined using method described in reference [11].

*** Based on previous measurement [7]. Present material splatters in test apparatus and, hence, cannot be measured.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A quarter-scale room fire test developed at NBS was used to help develop a preliminary approach for fire hazard assessment of wall-ceiling combinations of hull insulation materials. The quarter-scale test has been refined to include measurement of heat release rate, smoke, and carbon monoxide. In addition, polyphosphazene foam insulations were evaluated with this test.

The quarter-scale test was also modified for testing mattress insert materials, including polyphosphazene foam. Existing tests, used for measuring total heat, rate of heat release, and smoke production, were also used to evaluate these materials. Heat release rate measurements with the Ohio State University apparatus and smoke measurements with the ASTM E 662 test, modified for horizontal placement of specimens, gave adequate evaluation of the fire hazards of mattress insert materials.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Fire hazards assessment; foam (materials); heat release rate; hull insulation: interior finishes; mattresses; polyphosphazene foams; small scale fire tests; smoke.

13. AVAILABILITY

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